# Flavor in the Era of the LHC

*Sven Heinemeyer, IFCA (Santander)*

Benasque, 01/2010

1. Introduction

2. A little bit of history (on "Flavor in the Era of the LHC")

3. Examples for SuperB – LHC interplay

4. Impact of/for flavor observables on/from SUSY fits

5. Conclusions

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## 1. Introduction

- The SM has provided an accurate understanding of most experimental data
- However: the source of Electroweak Symmetry Breaking is still unclear
- There are many important questions the SM cannot answer:
  - Fermion mass hierarchies and mixing angles (quarks and leptons)
  - Nature of neutrino masses
  - Origin of the matter-antimatter asymmetry
  - Source of Dark Matter

⇒ the first three are related to the understanding of flavor and CPV

## The (more or less) official (optimistic?) LHC time line:

03/2010: first collisions at record breaking energy

2010: $\lesssim 0.05$ fb$^{-1}$ (at $\sqrt{s} = 7$ TeV)

2011: $\lesssim 1$ fb$^{-1}$ (at $\sqrt{s} = 7$ TeV) $\Rightarrow$ first physics results?

2012: shutdown, further splice checks, repairs, . . .

2013 – 2015: 10 fb$^{-1}$ per year $\Rightarrow$ physics results with "low" luminosity

2016: shutdown, preparation for "high luminosity"

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2020: upgrade to SLHC?

2021 + X (X > 0): SLHC?

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**WE LIVE IN AN EXCITING TIME!!!**

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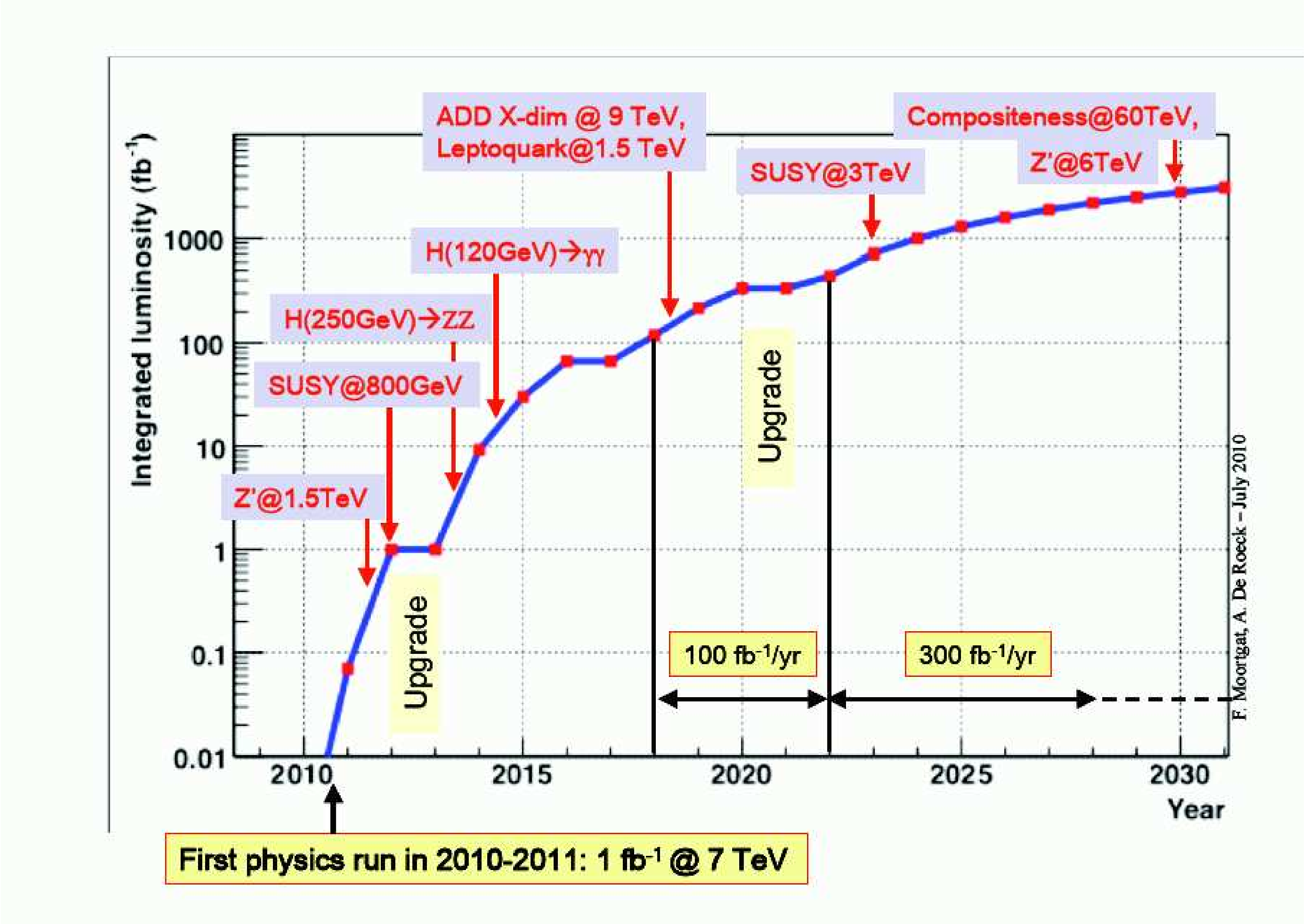
**WE HAVE TO PUT SUPER-B IN PERSPECTIVE WITH THE LHC RESULTS!**

# LHC experimental expectations: [A. De Roeck et al. '10]



# What will the LHC Era bring us?

- Detailed information about physics at the TeV scale
- Origin of fermion and gauge boson masses (EWSB) will be revealed
- Missing energy signatures at the LHC may reveal the production of DM
  $\longrightarrow$ measurement of its characteristics
- LHCb and super B-factories will provide accurate information on flavor physics
  $\Rightarrow$ complementary information on new physics?
- Search for (charged) lepton number violation (and $0\nu 2\beta$) could reveal the nature of neutrinos
  $\Rightarrow$ complementary information on new physics?
- Direct and indirect DM detection experiments will find some signal . . . ?
- The next years could be finally the end of the “SM dictatorship”

## Flavor observables are very sensitive to New Physics

There are some historical precedents within the SM:

- Charm was "discovered" via its effects on flavor ($K$) physics
- Evidence of the presence of the top quark was first seen via its effects on $B$ physics
  (and on electroweak precision observables)
- Large $B$–$\bar{B}$ mass difference: first evidence of very heavy top quark

$\Rightarrow$ Similar effects from new physics at the TeV scale could be expected

## (Guaranteed) LHC measurements in the context of flavor:

1. redtop properties:
   - top charge
   - top polarization
   - anomalous $Wtb$ couplings
   - rare top decays
   - (new) top resonances
   - ...

2. bottom properties (strong impact of LHCb!
   - cross sections of $b$ productions
   - lifetime and decays of $B$ mesons
   - baryons with $b$ quarks
   - spectroscopy
   - $B$ oscillations, CPV, ...
   - new physics via rare decays
   - ...

## Interplay of high-$p_T$ and low-energy flavor physics:

There are two main roads to explore BSM physics:

1. High-energy experiments (the high-energy frontier)
   $\Rightarrow$ What is the energy scale of New Physics?
   What are its (gross?) features?

2. High-precision low-energy experiments (the high-intensity frontier)
   $\Rightarrow$ What is the symmetry structure of the new degrees of freedom?

$\Rightarrow$ Natural interplay of these two approaches in constraining BSM physics

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In general this interplay can be fully explored only if specific NP models are selected

$\Rightarrow$ explicit evaluation of correlation(s) between high-$p_T$ and low-energy effects

$\Rightarrow$ SUSY is the best worked-out example . . .

## Old(?) questions from SuperB concerning LHC interplay:

(taken from talk by Marco Ciuchini, 04.12.2007)

* SUPERB PERFORMANCE ON BENCHMARKS IN MFV: for example, how large are the flavour signals in CMSSM/mSUGRA at a point in the parameter space (e.g. a snowmass point) which is visible at LHC?

⇒ we come back to this later . . .

## 2. A bit of history

There was a workshop 2006/2007:

**"Flavour in the Era of the LHC"**

(and a continuation 2008 – ??)

working groups:

1.) Collider aspects of flavour physics at high $Q^2$

2.) $B$, $D$ and $K$ decays

3.) Flavour physics of lepton and dipole moments

$\rightarrow$ working groups 1 and 2 had dedicated "interplay" subgroups

Topics of the subgroup (of working group 2):

– get an overview about existing tools

– develop ideas for integration of different tools

– facilitate the interplay of high $Q^2$ and low-energy $B$-physics

– ...

# On the importance of the interplay of high $Q^2$ and low-energy $B$-physics:

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**A:** Measure as much as possible

1. Direct discoveries/measurements (masses, mixing angles, . . . )
2. Electroweak precision observables ($M_W$, $m_t$, . . . )
3. Flavor-related observables ($B$, $D$, $K$ physics, . . . )
4. Astro-physical observables (CDM density, . . . )
5. . . .

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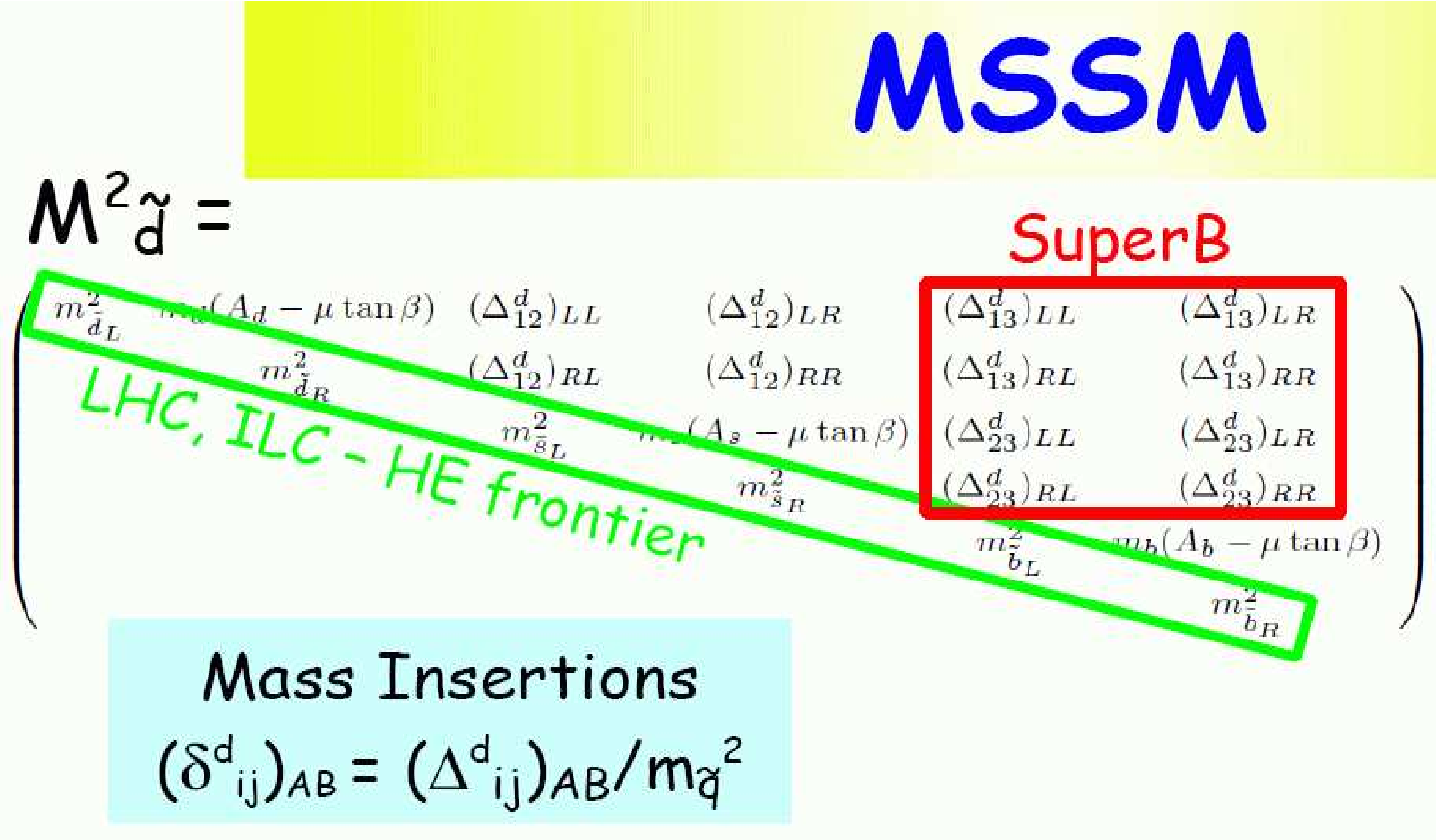
⇒ Interplay of the various observables/measurements ?
⇒ combination of tools
⇒ combination of benchmarks

# Example: NMFV MSSM

("my" NMFV: non-zero off-diagonal entries at low energies)

[*taken from M. Ciuchini '07*]



## Collection of tools:

- codes for low-energy observables (with flavor input)
- codes for high-energy observables (with flavor input)
- codes for the calculation of amplitudes
- codes for connecting the GUT and the (flavor)experimental scale
- codes to pass parameters/results from one code to another
- codes for UT/CKM fits
- codes to facilitate the interplay

⇒ the last one is the relevant here - and the most complicated?

## General questions:

- What is still missing? Are all relevant fields covered?
- How can it be ensured that code/calculation is useful for others?
- Can experimentalists make use of them?
- What are the wishes of the experimentalists?
- Interaction between theory and experiment?

## Concerning the interplay issue:

In order to work out the interplay one needs
consistent predictions for flavor and high-$p_T$ observables

$\Rightarrow$ combination of tools/calculations/. . .

**Q:** How can one connect different calculations/tools such that

– input/output is compatible
– (combination of) tools can be used by non-experts
(non-expert = non-author of the code)
$\Rightarrow$ mostly in the hands of the authors . . .

**A:** Two examples (success stories?):

1) Interface code that handles input/output $\rightarrow$ SLHA & FLHA
2) "Über-code" that interfaces various single codes
example: MasterCode (incl. some physics later)

1. SLHA = SUSY Les Houches Accord

   [*P. Skands et al. '03 - '10*]

   → Collection of rules to unambiguously define input/output
   for SUSY (MSSM, NMSSM, CPV, NMFV, . . . )

   ASCII file with clear BLOCK structure

   → widely used, well established

2. FLHA = Flavor Les Houches Accord

   [*N. Mahmoudi et al. '10*]

   → Collection of rules to unambiguously define input/output
   for flavor observables

   → 100% model independent!

   Exactly the same BLOCK structure as SLHA

   → quite new, usefulness will (hopefully) be seen in the near future

FLHA and SLHA can be used together or independently

## A few words on the “MasterCode”

⇒ collaborative effort of theorists and experimentalists
[*O. Buchmüller, R. Cavanaugh, D. Colling, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, SH, G. Isidori, K. Olive, S. Rogerson, F. Ronga, G. Weiglein*]

Über-code for the combination of different tools:

– tools are included as subroutines
– compatibility ensured by collaboration of
authors of “MasterCode” and authors of “sub tools”
– one “MasterCode” for one model . . .

⇒ evaluate observables of one parameter point consistently
with various tools

Example: flavor observables and high $p_T$ observables
can be combined

⇒ CRUCIAL POINT of “Flavor in the LHC era”

## Status of the "MasterCode":

– one model: (MFV) MSSM (see next section)

– tools included:
  – $B$-physics observables *[SuFla]*
  – more $B$-physics observables *[SuperIso]*
  – Higgs related observables, $(g-2)_\mu$ *[FeynHiggs]*
  – Electroweak precision observables *[FeynWZ (SUSYPope)]*
  – Dark Matter observables *[MicrOMEGAs, DarkSUSY]*
  – for GUT scale models: RGE running *[SoftSusy]*

⇒ all most-up-to-date codes on the market!

– added: $\chi^2$ analysis code *[Minuit]*

– currently being implemented:
  – Higgs constraints (for $\chi^2$ contributions . . . ) *[HiggsBounds]*

– planned: inclusion of more tools / more models

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⇒ all most-up-to-date codes on the market! ⇒ crucial for precision!

– added: $\chi^2$ analysis code *[Minuit]*

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## $B/K$ physics observables in the MasterCode

1. BR($b \to s\gamma$)

2. BR($B_s \to \mu^+\mu^-$)

3. $\Delta M_s$

4. R($\Delta M_s/\Delta M_d$)

5. BR($B_u \to \tau\nu_\tau$)

6. BR($B \to X_x \ell^+\ell^-$)

7. R($K \to \ell\nu$)

8. R($\Delta M_K$)

$\Rightarrow$ largest impact: (1) and (2) $\Rightarrow$ some examples later

## The other "old workshop" issue: Benchmarks

a set of parameter points in a (your favorite) model (beyond the SM)

- Required for BSM searches at colliders (past, present, future)
  $\longrightarrow$ often it is not feasible to scan over all parameters

- Map out the characteristics of the parameter space

- Take into account all(?) possibilities

- Ensure compatibility with all(?) current bounds
  - searches for new particles
  - (low-energy) flavor bounds
  - (low-energy) electroweak precision bounds
  - cold dark matter
  - ...

Benchmarks can be used to:

- Study the performance of different detectors
- Study the performance of different experiments
- Perform very detailed studies
- Analyzing the complementarity of different experiments
- Work out synergy effects of different experiments
  (in other words again: the interplay )

Prime example from the past: SPS (Snowmass points and slopes)
(especially SPS 1a)
[*hep-ph/0202233*]

Note: Once new physics will have been found, benchmarks become more and more obsolete

However: so far we might still want to consider them

Possible approach for SUSY:

Find/use points (in the (N)MFV MSSM ) that are compatible with
- direct experimental searches
- flavor physics constraints
- precision observables constraints
- ...

⇒ study the complementarity of the low/high-energy experiments

⇒ study the synergy of the low/high-energy experiments

i.e. combine results from all sources to pin down the (N)MFV MSSM

. . . but this seems to be very difficult

# 3. Examples for SuperB – LHC interplay

⇒ study the complementarity of the low/high-energy experiments

⇒ study the synergy of the low/high-energy experiments

Three approaches/results:

1. Take the good old SPS points
   some of them have been studied in quite detail
   → evaluate LHC measurements
   ⇒ investigate what $B$-physics can add ⇒ SuperB activities
2. Take a GUT based model without flavor violation
   → fit to current data
   → fit to anticipated LHC data
   ⇒ investigate what $B$-physics can add (in the future)
   ⇒ see next section
3. Take a GUT based model with flavor violation
   → fit to current data
   → fit to anticipated LHC data
   ⇒ investigate what $B$-physics can add (in the future)
   not realized yet . . . possible models?

## First example:

→ work done some time ago for previous SuperB workshop, application of the MasterCode

## Main idea:

### Assumptions:

– LHC has collected 300 $\text{fb}^{-1}$
– CMSSM is a good description of observed data
– no (clear) sign of NMFV at the LHC
– data favors a certain SPS point

### Impact of SuperB?

– Predictions for flavor observables?
– Can these predictions be constrained by SuperB?
– Can SuperB restrict the NMFV parameters?

# Assumption (I): SPS1a realized ("typical" CMSSM scenario)

LHC friendly (light) spectrum

cascades possible:
$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R \ell q \to \tilde{\chi}_1^0 \ell\ell q$

edge measurements:

$$(m_{\ell\ell}^2)^{\text{edge}} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

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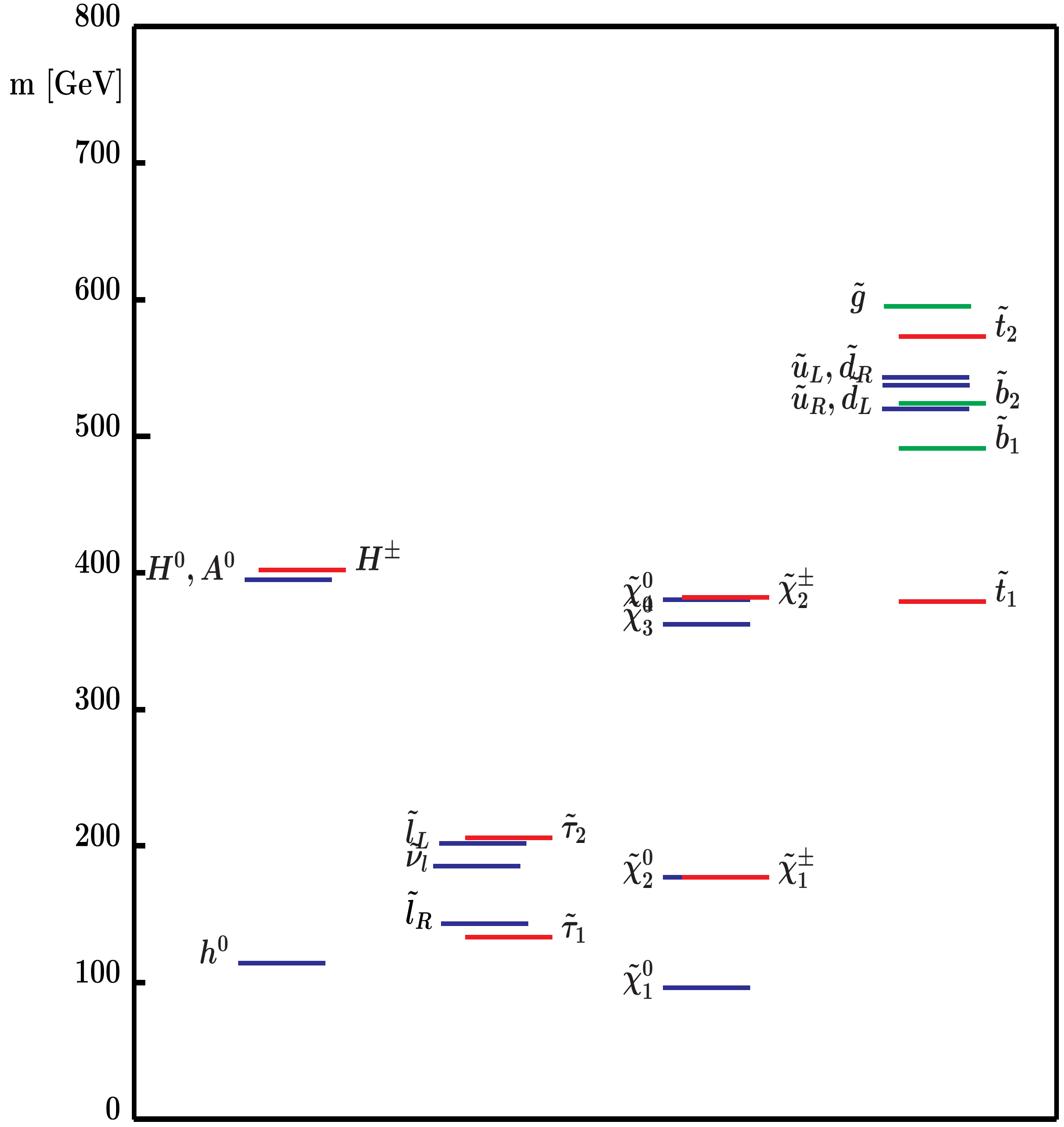
$$(m_{q\ell}^2)^{\text{edge}}_{\text{min}} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{l}_R}^2)}{m_{\tilde{l}_R}^2}$$



# Assumption (I): SPS1a realized ("typical" CMSSM scenario)

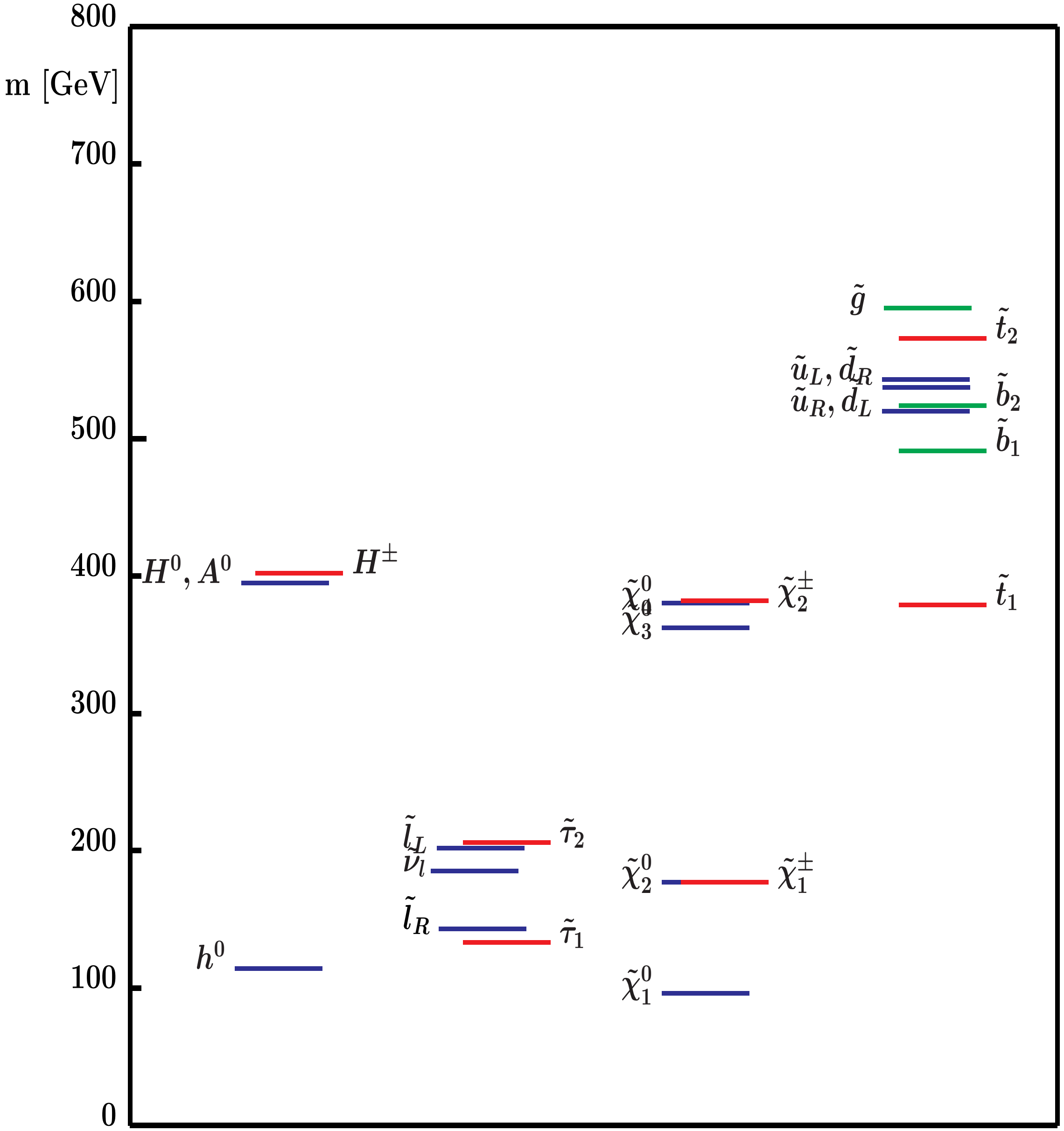
Results based on 300 $\text{fb}^{-1}$ (2014)

Edge measurements:

$$(m_{\ell\ell})^{\text{edge}} = 58.9 \pm 0.1 \text{ GeV}$$
$$(m_{q\ell\ell})^{\text{edge}} = 451.1 \pm 4.5 \text{ GeV}$$
$$(m_{q\ell})^{\text{edge}}_{\text{min}} = 317.5 \pm 3.1 \text{ GeV}$$

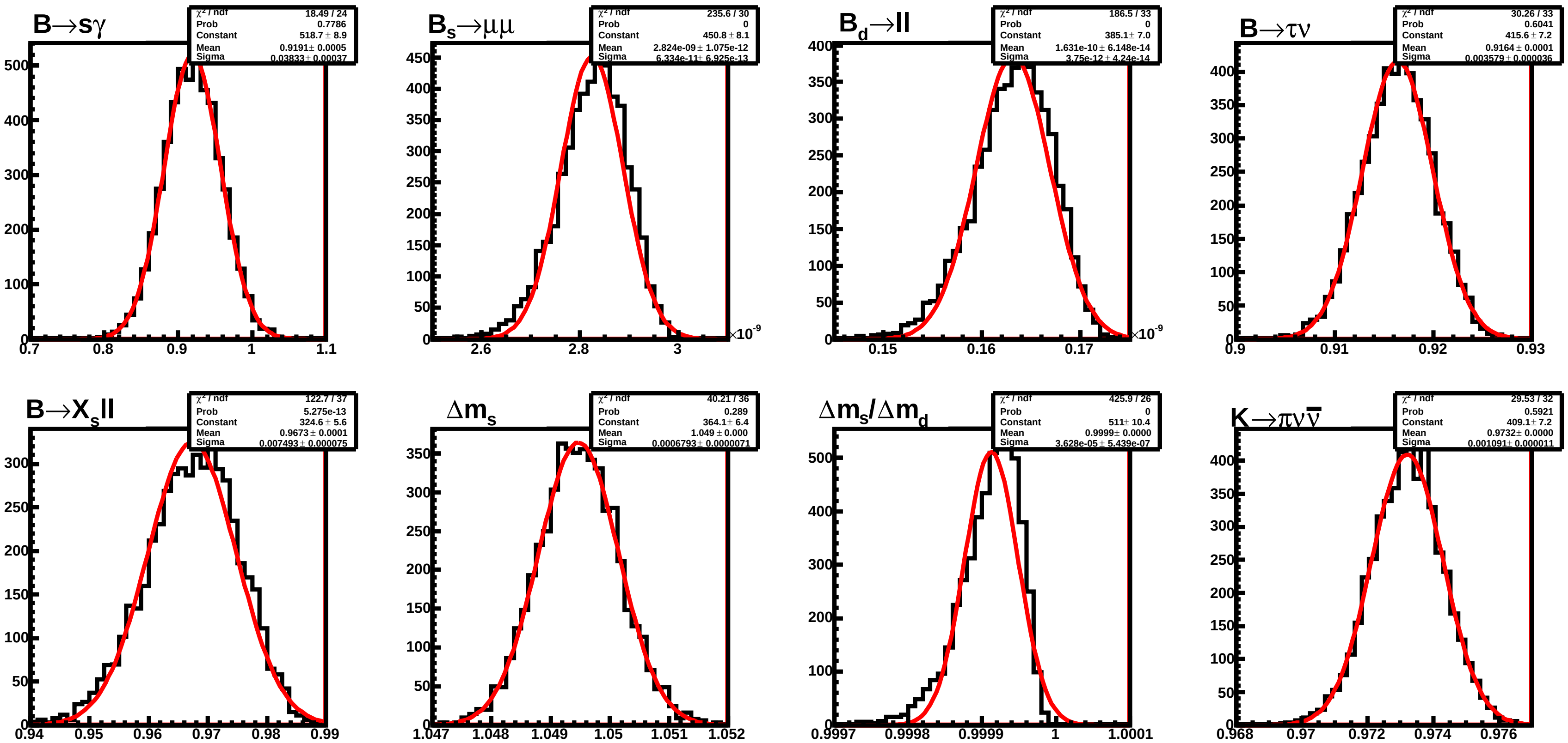
Combination with all other constraints:

$$m_{1/2} = 250.0 \pm 1.1 \text{ GeV}$$
$$m_0 = 100.0 \pm 1.5 \text{ GeV}$$
$$A_0 = 100 \pm 30 \text{ GeV}$$
$$\tan\beta = 9.8 \pm 1.2$$



## $\Rightarrow$ Strong impact of LHC constraints on (SPS1a) flavor sector:

Toy MC analysis for flavor observables:




## $\Rightarrow$ consistent prediction of flavor observables

⇒ Strong impact of LHC constraints on (SPS1a) flavor sector:

⇒ consistent prediction of flavor observables

no CKM uncertainties included ⇒ errors only from fit!

theory errors: $\sim 3\%$ $(K_L \to \pi^0 \nu\bar{\nu})$ . . . $\sim 25\%$ $(\Delta M_{B_s})$

$$\mathcal{R}(b \to s\gamma) = 0.919 \pm 0.038$$
$$\mathcal{R}(B_u \to \tau\nu_\tau) = 0.968 \pm 0.007$$
$$\mathcal{R}(B_s \to X_s \ell^+\ell^-) = 0.916 \pm 0.004$$
$$\mathcal{R}(B \to K\nu\bar{\nu}) = 0.967 \pm 0.001$$
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.824 \pm 0.063) \times 10^{-9}$$
$$\mathrm{BR}(B_d \to \mu^+\mu^-) = (1.631 \pm 0.038) \times 10^{-10}$$
$$\mathcal{R}(\Delta M_{B_s}) = 1.050 \pm 0.001$$
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⇒ SuperB could not see deviations if SPS1a (MFV) is realized

⇒ any deviation would prove NMFV!

# Assumption (II): SPS5 realized (CMSSM scenario with light $\tilde{t}$)

still LHC friendly (light $\tilde{t}$)

cascades possible:

$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R \ell q \to \tilde{\chi}_1^0 \ell\ell q$

edge measurements:

$$(m_{\ell\ell}^2)^{\text{edge}} = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}$$

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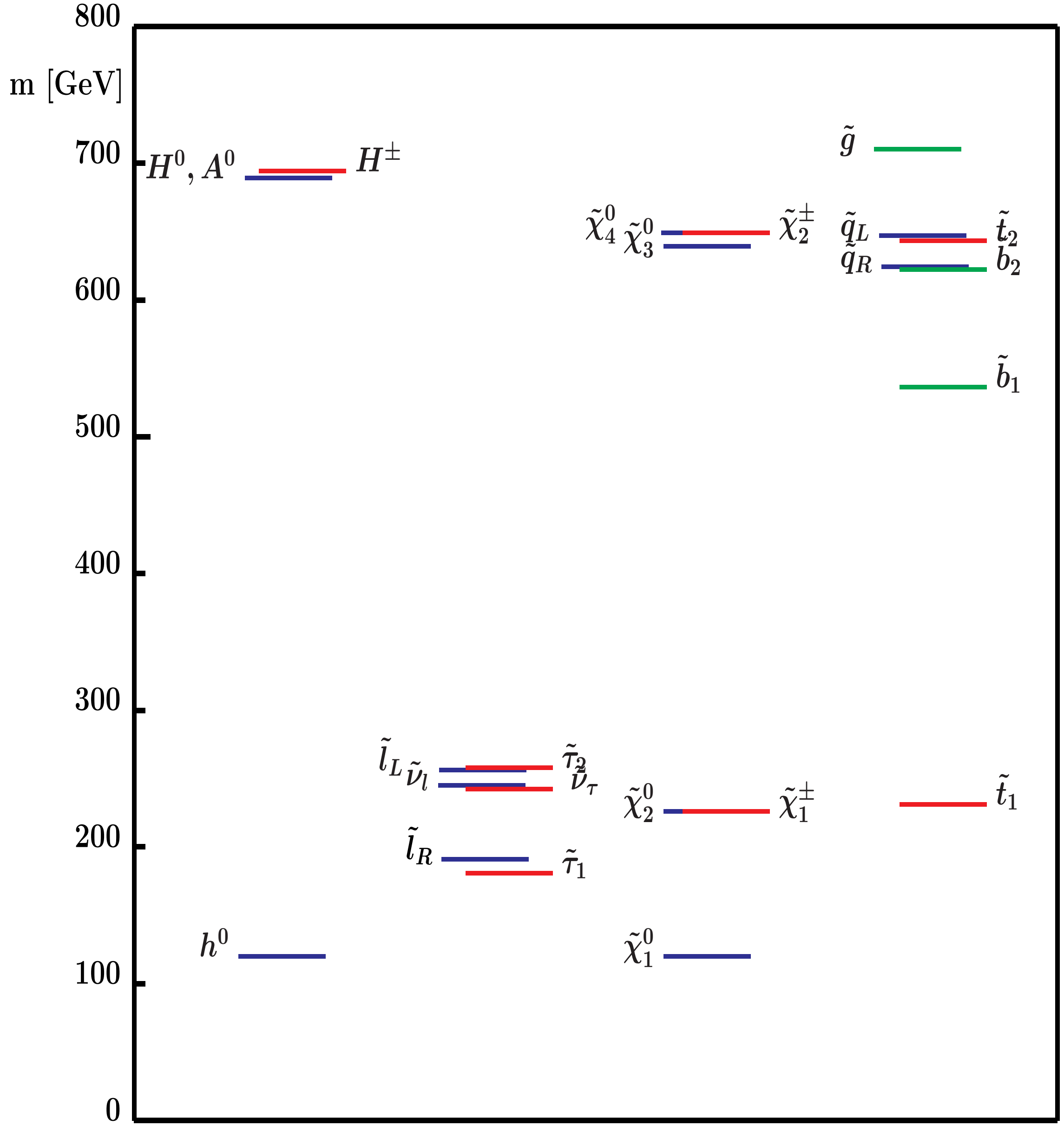

## ⇒ Strong impact of LHC constraints on (SPS5) flavor sector:

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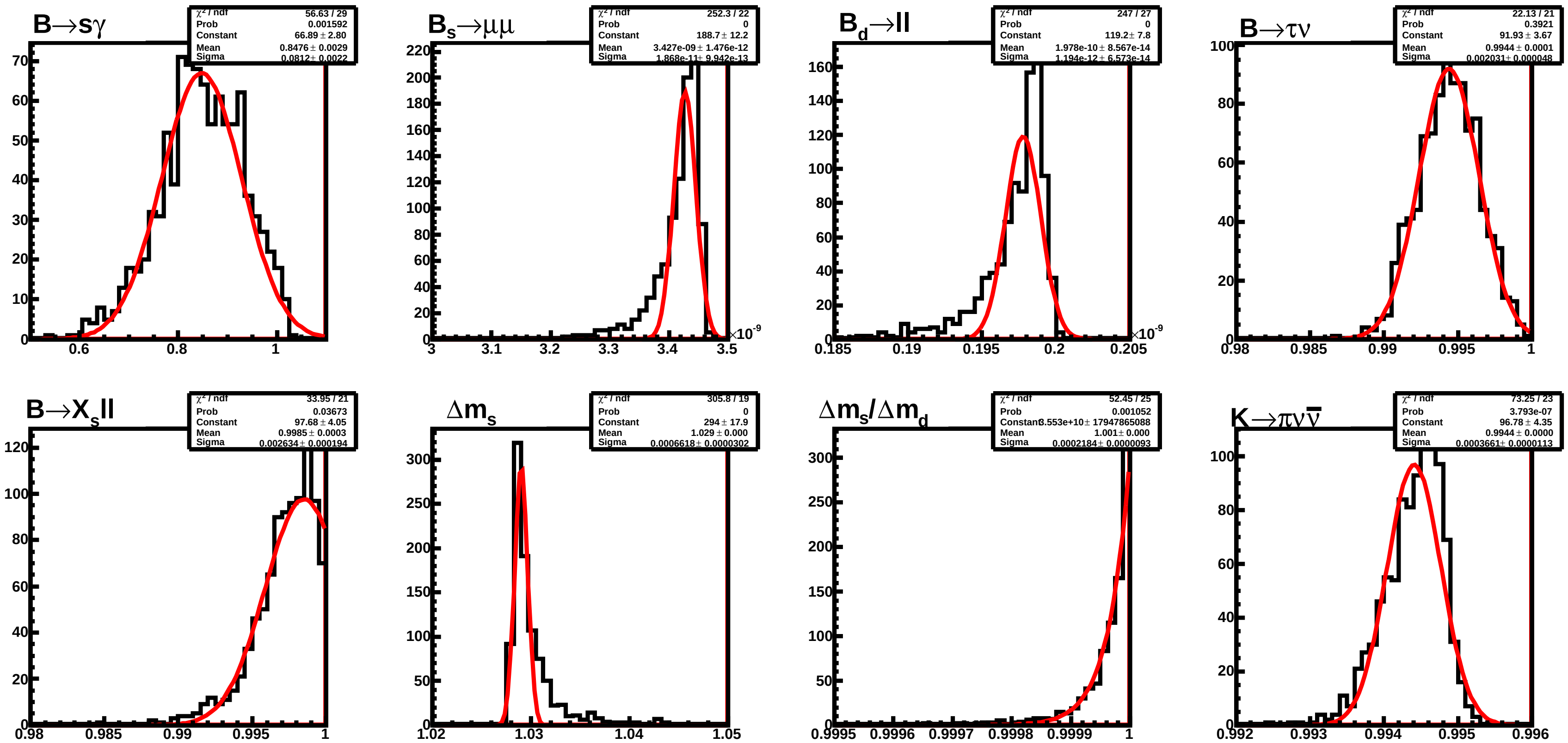


⇒ relatively consistent prediction of flavor observables

$\Rightarrow$ Strong impact of LHC constraints on (SPS5) flavor sector:

$\Rightarrow$ relatively consistent prediction of flavor observables

no CKM uncertainties included $\Rightarrow$ errors only from fit!

theory errors: $\sim 3\%$ $(K_L \to \pi^0 \nu\bar{\nu})$ ... $\sim 25\%$ $(\Delta M_{B_s})$

$$\begin{aligned}
\mathcal{R}(b \to s\gamma) &= 0.848 \pm 0.081 \\
\mathcal{R}(B_u \to \tau\nu_\tau) &= 0.997 \pm 0.003 \\
\mathcal{R}(B_s \to X_s \ell^+\ell^-) &= 0.995 \pm 0.002 \\
\mathcal{R}(B \to K\nu\bar{\nu}) &= 0.994 \pm 0.001 \\
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⇒ SuperB could not see deviations if SPS5 (MFV) is realized (exc. $b \to s\gamma$?)

⇒ any deviation would prove NMFV!

## 4. Impact of/for flavor observables on/from SUSY fits

– combine all electroweak precision data as in the SM
– combine with $B$ physics observables
– combine with CDM and $(g-2)_\mu$
– include SM parameters with their errors: $m_t$, $M_Z$, $\Delta\alpha_{\rm had}$

$\Rightarrow$ $\chi^2$ function

$\longrightarrow$ scan over the
full CMSSM/NUHM1 parameter space
$\sim 2.5\ 10^7$ points samples with MCMC

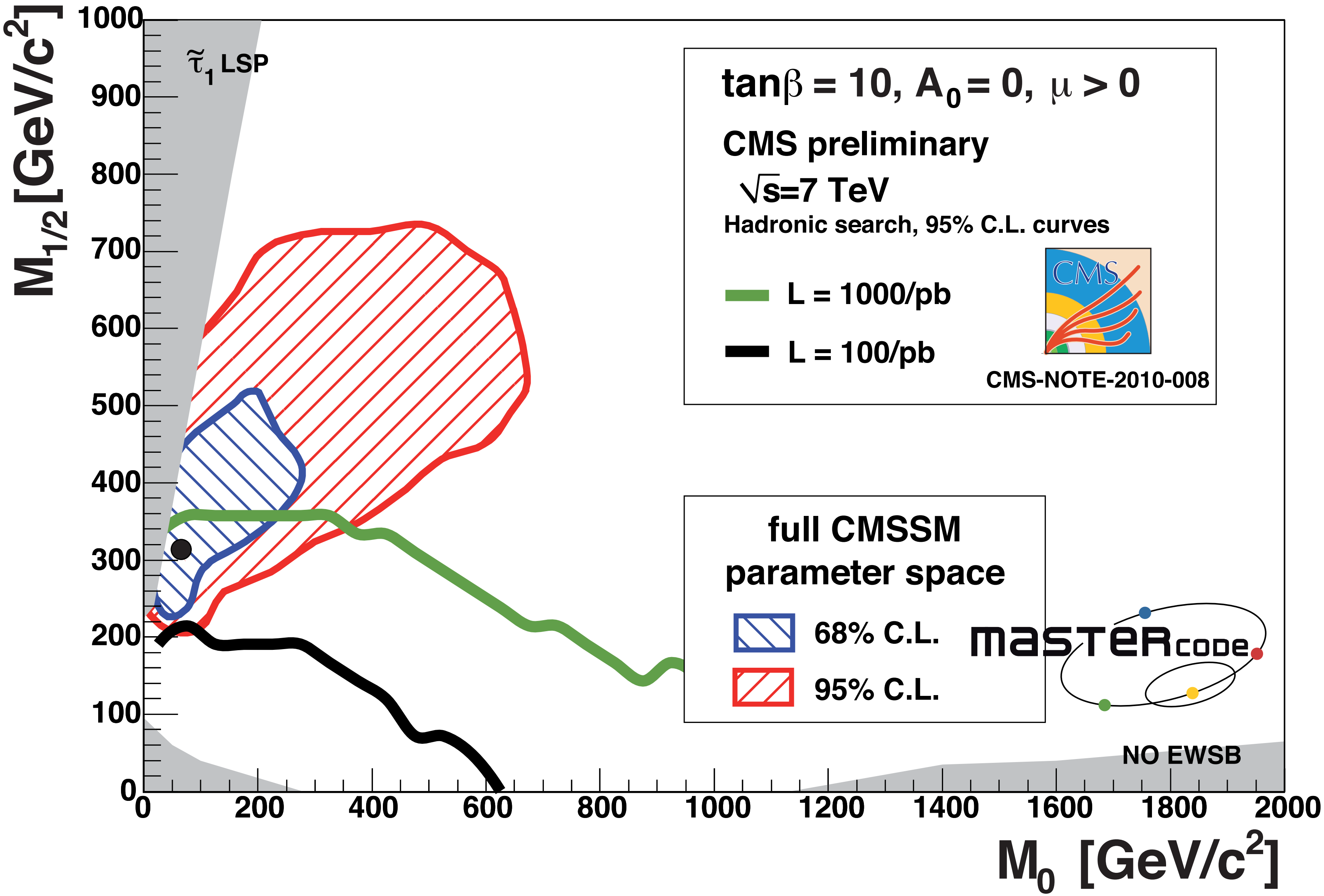
statistical measure: $\chi^2$ function (Frequentist, no priors)

$\longrightarrow$ final minimum: Minuit

$\Delta\chi^2$: 68, 95% C.L. contours

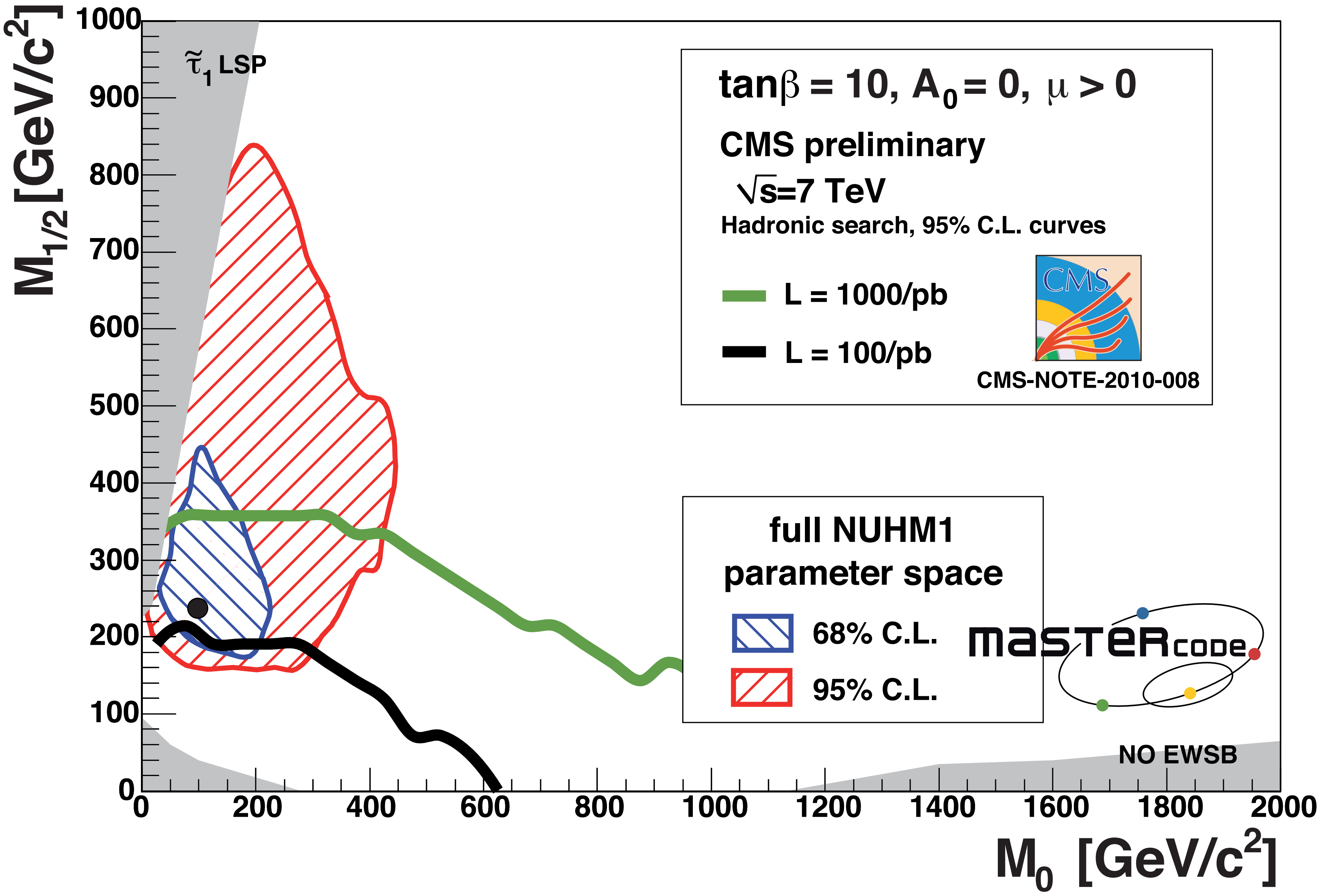
$\Rightarrow$ preferred CMSSM/NUHM1 parameters $\boxed{\Rightarrow \mathcal{L}_{\rm SUSY}}$
$\Rightarrow$ LHC reach; predictions for flavor observables

# LHC (CMS) ⊕ CMSSM analysis:




⇒ best-fit point and part of 68% C.L. are can be tested in 2011

## LHC (CMS) ⊕ NUHM1 analysis:

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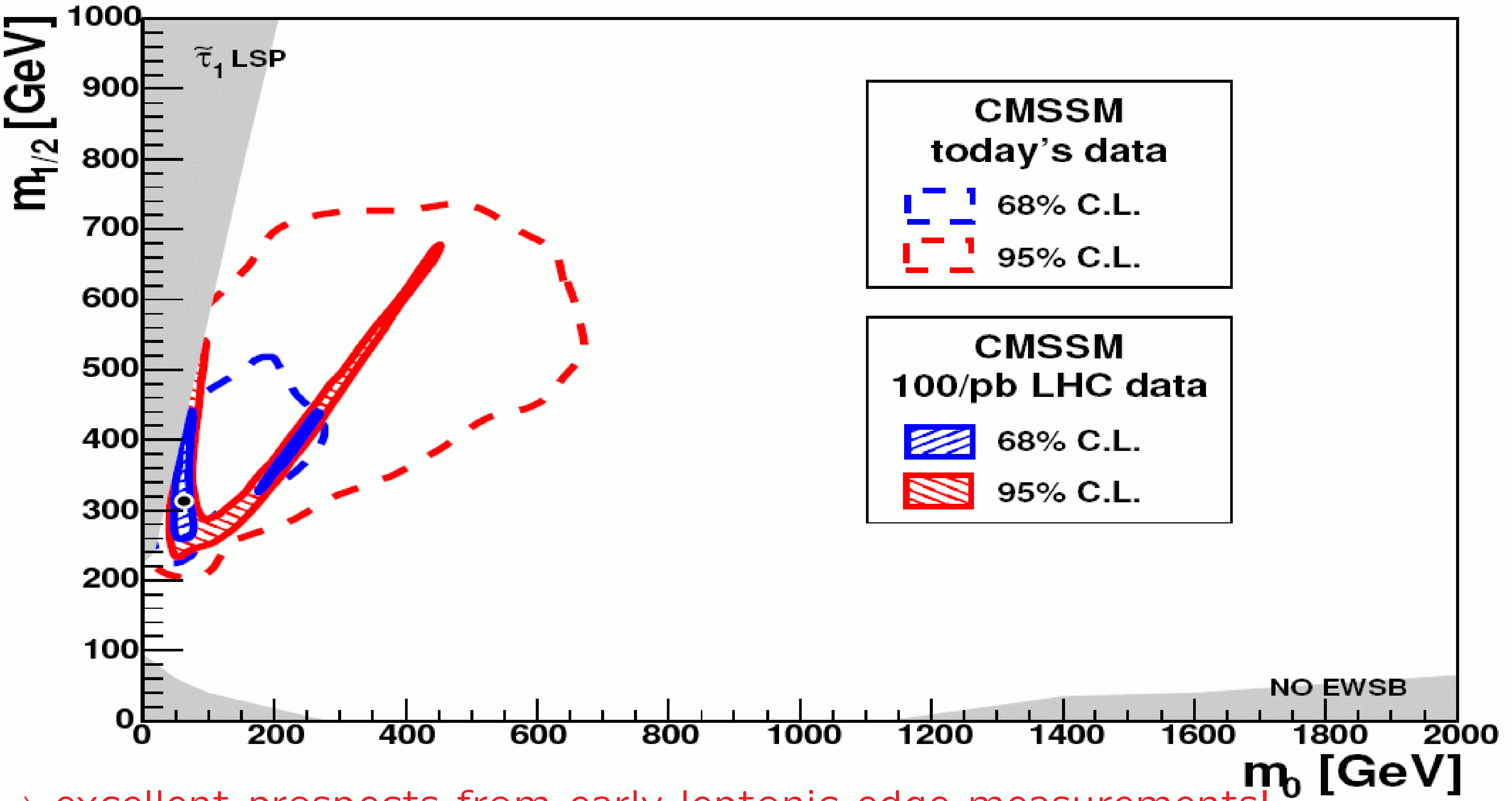
# LHC (CMS) impact with 0.1 $fb^{-1}$:

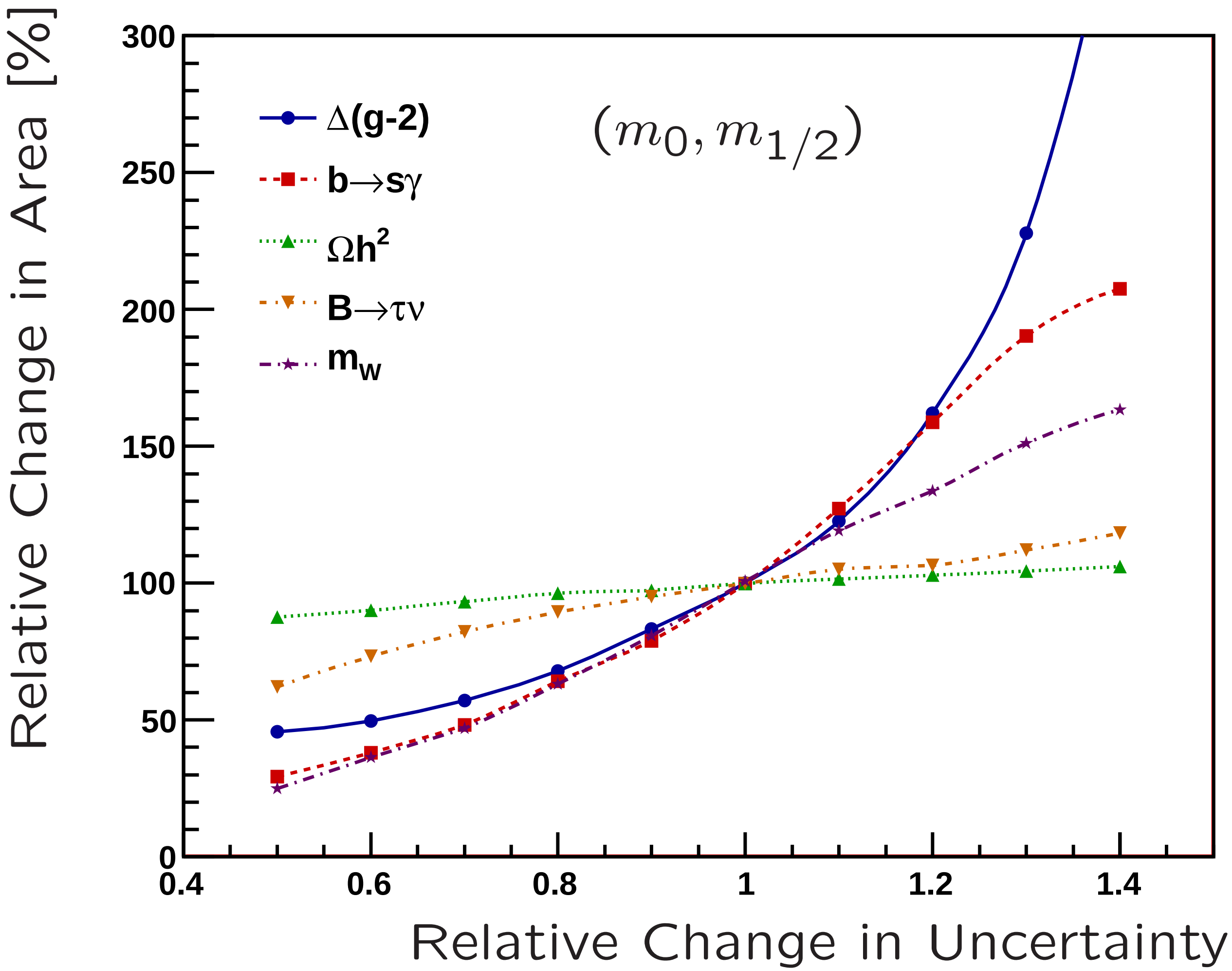
[2008]

CMSSM analysis incl. leptonic edge measurements




$\Rightarrow$ excellent prospects from early leptonic edge measurements!

# Impact of $B$ physics observables (CMSSM):




⇒ strong impact of BR($b \to s\gamma$)

⇒ moderate impact of BR($B_u \to \tau\nu_\tau$)
(but more potential for improvement?)

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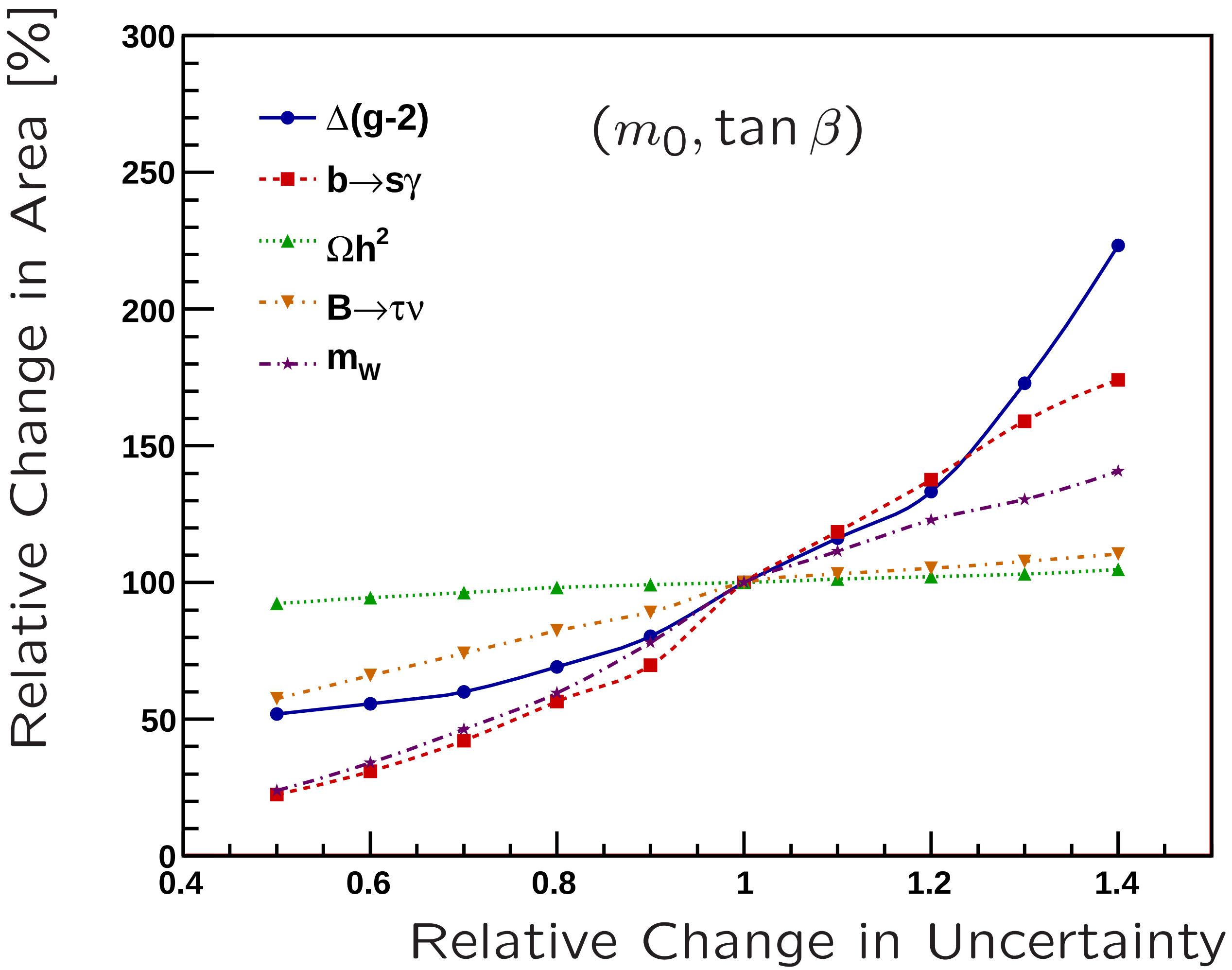
[2009]

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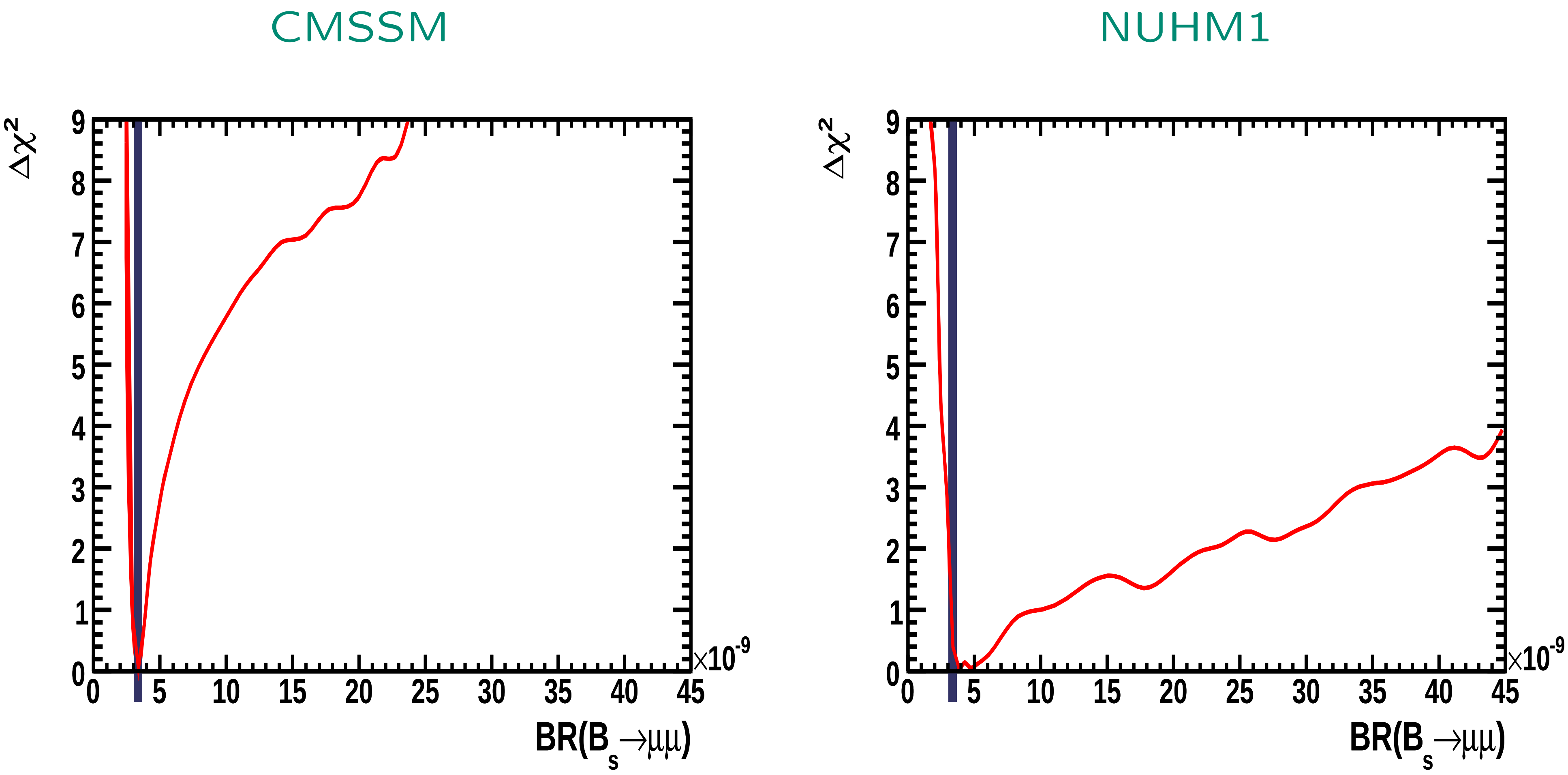
## Fit predictions for $B$ physics observables: $\mathrm{BR}(B_s \to \mu^+\mu^-)$

[2009]




$\Rightarrow$ best-fit similar to SM, larger value would favor NUHM1

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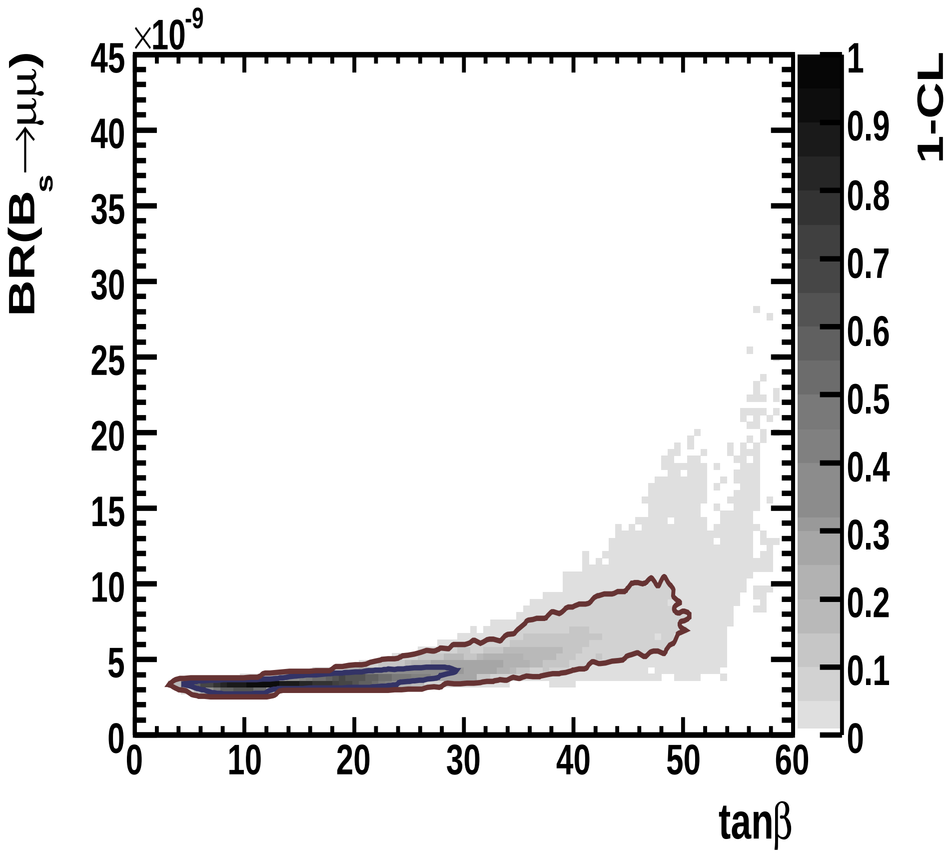
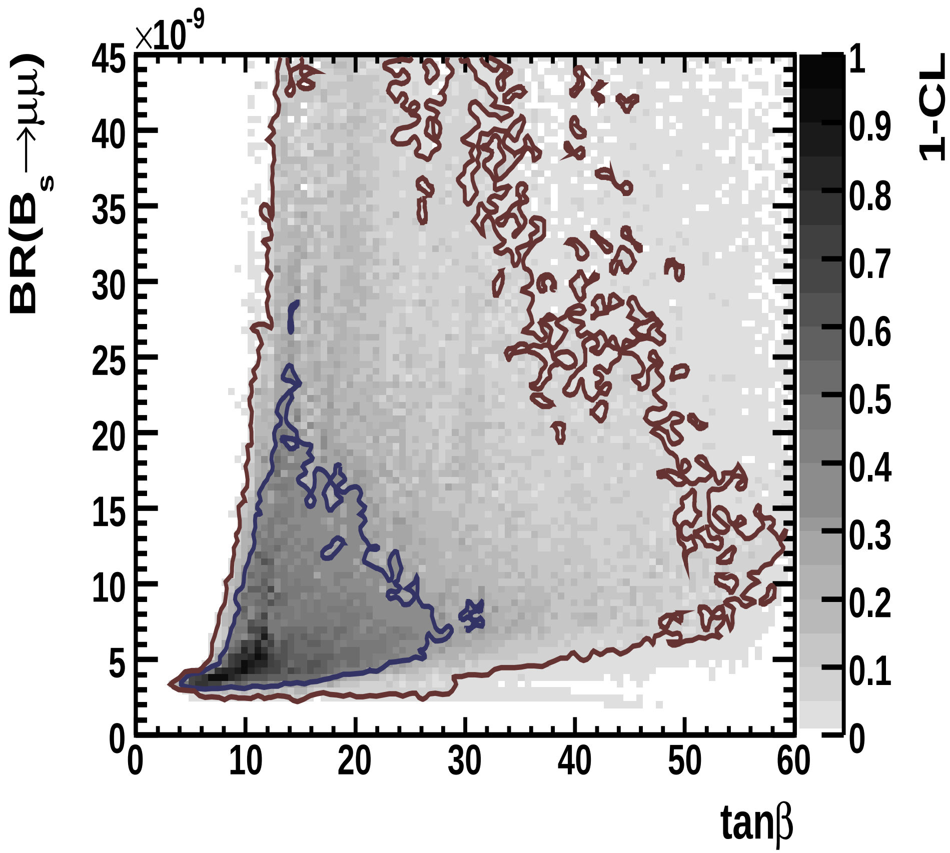
[2009]

CMSSM




NUHM1

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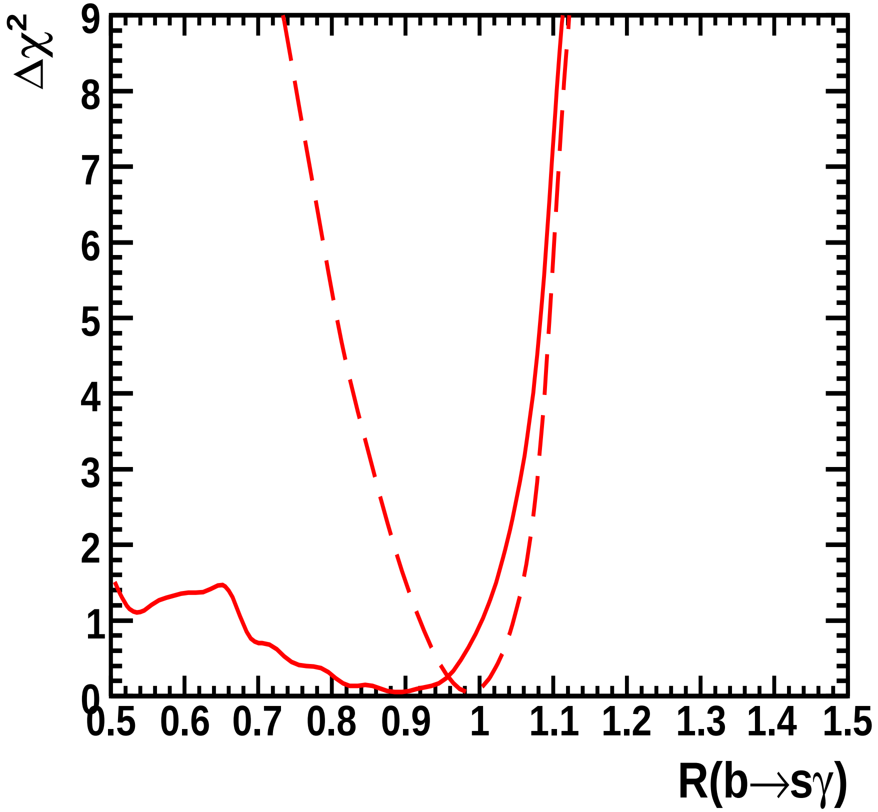
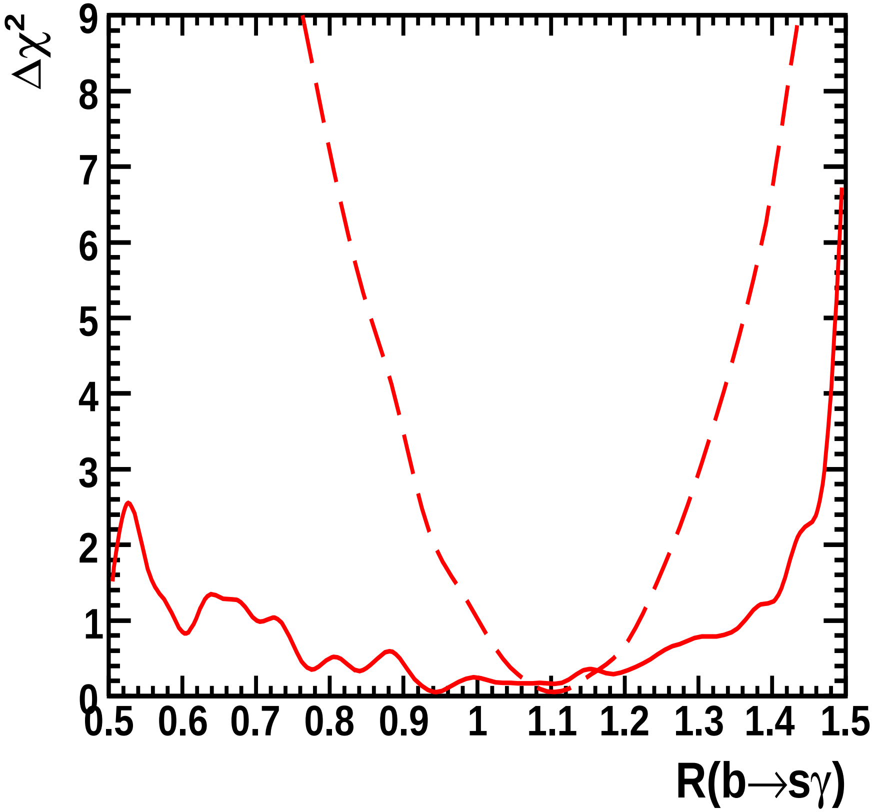
[2009]

CMSSM




NUHM1




solid: exp. data not included; dashed: exp. data included

$\Rightarrow$ best-fit similar to SM, but strong constraint in the fits

## 5. Conclusions

- SuperB has to be view in context of the LHC

- What kind of interplay and/or synergy can be established?

  ⇒ can be worked out only(?) in concrete models

- Combination of tools for high-$p_T$ and flavor observables?
  Examples for interfaces: SLHA and FLHA

- SuperB – LHC interplay:
  – take a benchmark point (e.g. SPS 1a)
  – evaluate LHC measurements
  – investigate what $B$ physics can add

  ⇒ SPS 1a and SPS 5 studied: only deviations could be measured

- Impact of/for flavor observables on/from SUSY fits:
  – strong impact of BR($b \to s\gamma$), less of BR($B_u \to \tau\nu_\tau$)
  – clear predictions for $B$ physics observables ⇒ clear tests of the model

Back-up

Collection of tools:
(ordered roughly thematically)

Code # 1:
Name: no name [*Silvestrini*]
Description: $K\bar{K}$ mixing, $B_{(s)}\bar{B}_{(s)}$ mixing, $b \to s\gamma$, $b \to s\, l^+ l^-$ in NMFV MSSM
Availability: planned

Code # 2:
Name: SuFla [*Isidori, Paradisi*]
Description: low-energy flavor observables in the MFV MSSM
Now included: BR($b \to s\gamma$), $\Delta M_{B_s}$, BR($B_s \to \mu^+\mu^-$), BR($B_u \to \tau\nu_\tau$), BR($B_s \to X_s \ell\ell$), BR($K \to \tau\nu_\tau$), $\Delta m_K$, BR($K \to \pi\nu\nu$), BR($B_d \to \ell\ell$)

Code # 3: XSusy [*Bozzi, Fuks, Herrmann, Klasen*]
Description: masses, production cross sections, BR in NMFV MSSM
Availability: partially (partial SLHA2 compatibility)

Code # 4:
Name: SuperIso [*Mahmoudi*]
Description: all kind of flavor observables at low-energies
in various models (SM, THDM, MSSM, . . . )
Availability: yes

Code # 5:
Name: SusyBSG [*Degrassi, Gambino, Slavich*]
Description: BR($b \to s\gamma$) in the MFV MSSM (highest precision)
Availability: yes (web page)

Code # 6:
Name: no name [*Bobeth, Ewerth, Haisch*]
Description: rare $B$ and $K$ decays in/beyond SM
Availability: planned

Code # 7:
Name: no name [*Chankowski, Jäger, Rosiek*]
Description: FCNC observables in MSSM
Availability: planned

Code # 8:

Name: FCHDECAY [*Bejar, Guasch*]

Description: FCNC Higgs decays in NMFV MSSM

Availability: yes (web page)

Code # 9:

Name: FeynHiggs [*Hahn, SH, Hollik, Rzehak, Weiglein*]

Description: Higgs/EWPO phenomenology in the (N)MFV (complex) MSSM

Availability: yes (manual, web page, $\oplus$ on-line version)

Code # 10:

Name: no name [*Bejar, Guasch*]

Description: FC Higgs/top decays in 2HDM I/II

Availability: planned

## Code # 11:

Name: FeynArts/FormCalc [*Hahn*]

Description: (arbitrary) one-loop corrections in (N)MFV MSSM

Availability: yes (manual, web page)

## Code # 12:

Name: SLHALib2 [*Hahn*]

Description: read/write SLHA2 data, i.e. NMFV/RPV/CPV MSSM, NMSSM

Availability: yes (manual, web page)

$\longrightarrow$ same needed for FLHA (see above)

Code # 13:

Name: Spheno [*Porod*]

Description: evaluates NMFV MSSM parameters from GUT scale input

Availability: yes (manual, web page)

Code # 14:

Name: SoftSUSY [*Allanach*]

Description: evaluates NMFV MSSM parameters from GUT scale input

Availability: yes (manual, web page)

Code # 15:

Name: MicrOMEGAs [*Belanger, Boudjema, Pukhov, Semenov*]

Description: CDM density, some $B$-physics observables in MFV MSSM

Availability: yes (manual, web page)

Code # 16:

Name: UTfit

Description: Unitarity Triangle fits (Bayesian), in SM and beyond

Availability: yes (web page)

Code # 17:

Name: CKMFitter

Description: CKM fits (Frequentist), (mostly) in SM

Availability: yes (web page)

⇒ all codes including short description are included in the write-up for the LHC/Flavor workshop

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Availability: yes (web page)

⇒ all codes including short description are included in the write-up for the LHC/Flavor workshop

Code # 18:

Description: combination of various tools (⇒ interplay!)

⇒ see below (now above! :-)

## Other codes:

not mentioned so far, since no flavor related models/observables are used/calculated

However: still relevant for interplay

Name: DarkSUSY [*Gondolo et al.*]

Description: CDM, $\sigma_\chi$ for direct DM detection

Availability: yes (manual, web page)

Name: Isajet/Isasusy [*Baer, Paige, Protopopescu, Tata*]

Description: MFV MSSM parameters from GUT scale input

Availability: yes (manual, web page)

Name: Suspect [*Djouadi, Kneur, Moultaka*]

Description: MFV MSSM parameters from GUT scale input

Availability: yes (manual, web page

# Other codes (II):

not mentioned so far, since no flavor related models/observables are used/calculated

However: still relevant for interplay

Name: FeynWZ [*SH, Hollik, Weber, Weiglein*]

Description: electroweak precision observables in the MFV (complex) MSSM

Availability: planned/partially public

Last(?) overview about SUSY related tools:

[*B. Allanach, hep-ph/0805.2088*]